

Impacts of Corrective Switching

Paula Lipka, Anya Castillo, John-Paul Watson,
Richard O'Neill, Shmuel Oren

June 24, 2014

Outline

- Introduction
- DC Example: Fixing line violations
- AC Example: 2 Bus Network
- AC Example: 3 Bus Network
- Conclusion

What can go wrong in the power system?

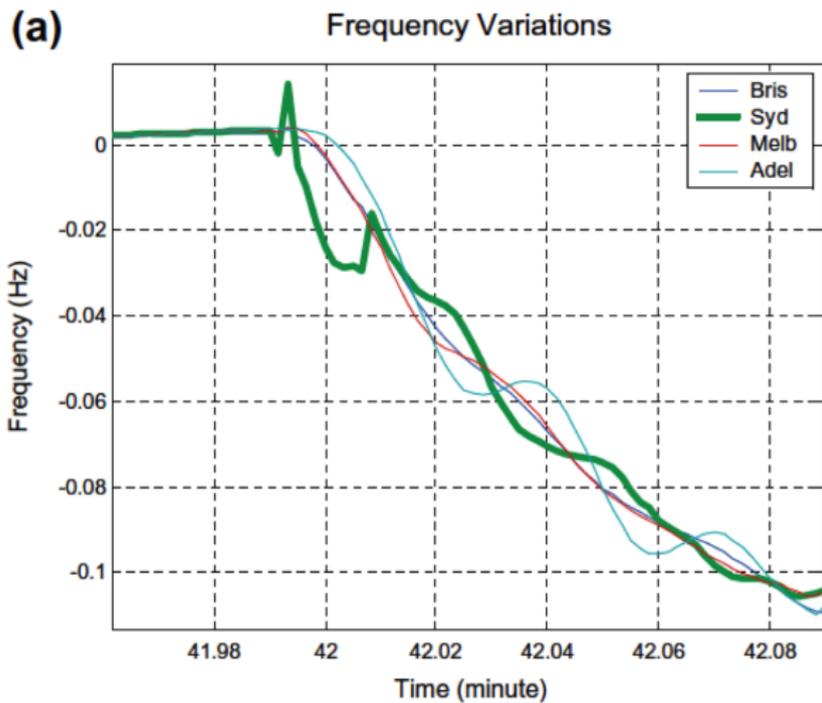
Generator Outages



Line Outages



What Happens?



What Other Problems Can Occur?

- Under/over voltage
- Load shedding
- Line overloading
- Transient instability of power or voltage

Resolving Contingencies and Other Problems

Considerations:

- Transient stability
- When to enforce security constraints
- Minimize load shed or total energy cost?

Strategies:

- FACTS devices (series)
- Shunt capacitance/inductance (parallel)
- Redispatch generation
- Phase angle
- Corrective Switching

Resolving Contingencies

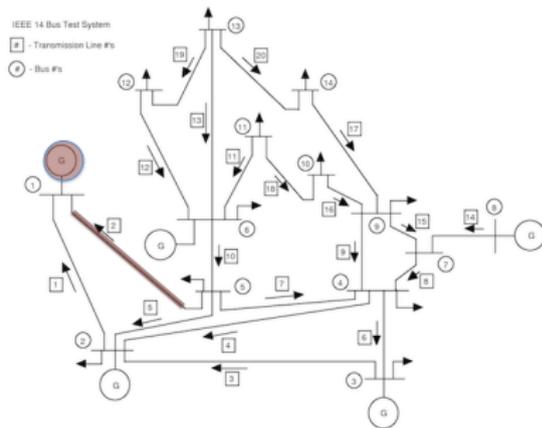
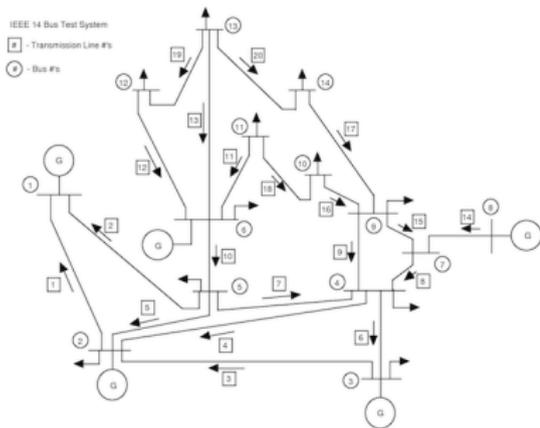
Considerations:

- Transient stability
- When to enforce security constraints
- Minimize load shed or total energy cost?

Strategies:

- FACTS devices (series)
- Shunt capacitance/inductance (parallel)
- Redispatch generation
- Phase angle
- **Corrective Switching**

What is Corrective Switching?



Questions....

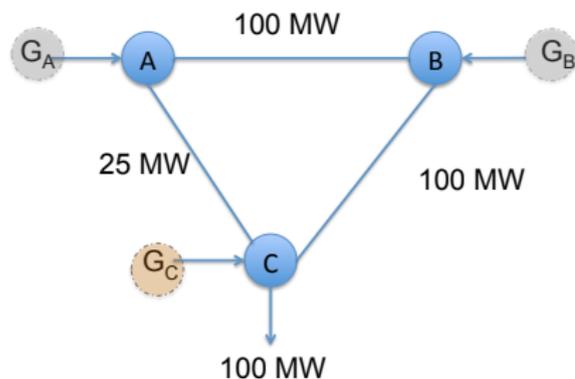
- How does an outage change the network solution?
- How does corrective switching help?

Outline

- Introduction
- DC Example: Fixing line violations
- AC Example: 2 Bus Network
- AC Example: 3 Bus Network
- Conclusion

DC with Line Limits: Is Redispatch Enough?

All generators have $P_g^{max} > 100$ MW. Generator C is the cheapest; A and B are the same price.
All lines have equal impedance



Line Limits on Power Transfer

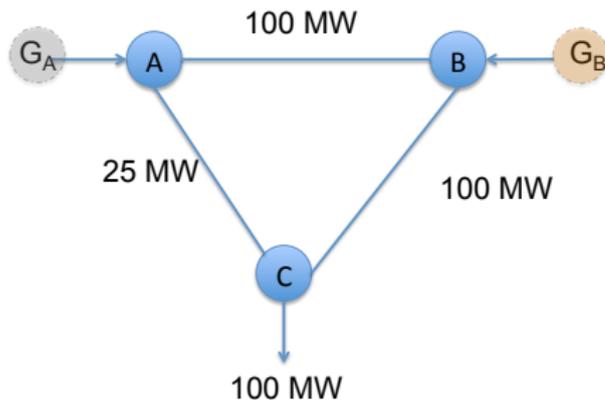
$$\underline{\text{A-B:}} \quad -100 \leq \frac{1}{3}G_A - \frac{1}{3}G_B \leq 100$$

$$\underline{\text{B-C:}} \quad -100 \leq \frac{1}{3}G_A + \frac{2}{3}G_B \leq 100$$

$$\underline{\text{A-C:}} \quad -25 \leq \frac{2}{3}G_A + \frac{1}{3}G_B \leq 25$$

DC with Line Limits: Is Redispatch Enough?

Contingency: Lose Generator C

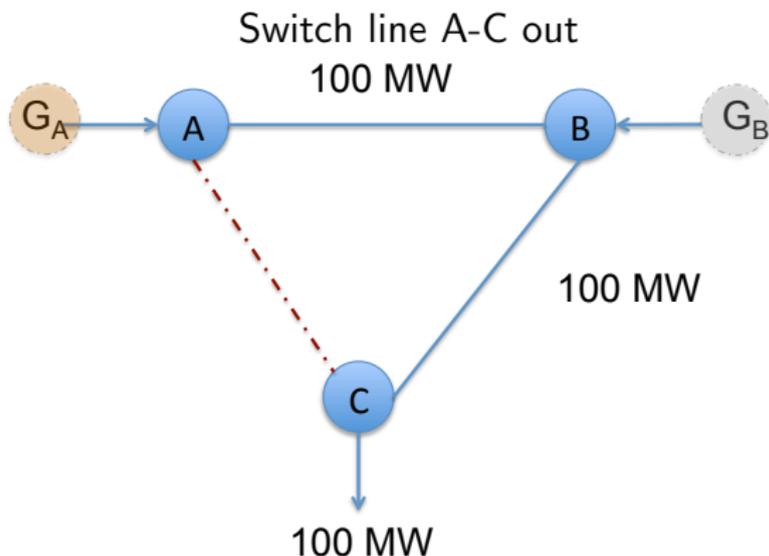


With Redispatch Only:

Due to constraint on line A-C:
Maximum power is when
 $G_B = 75 \text{ MW}$

Minimum load shed 25 MW

DC with Line Limits: Required Redispatch plus Corrective Switching

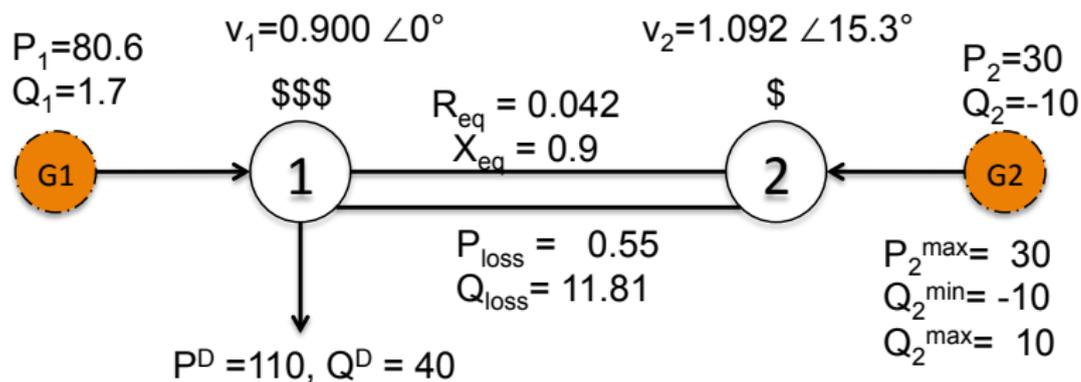


Switch line A-C out
Now, $G_A=100\text{MW}$; no load shed required

Outline

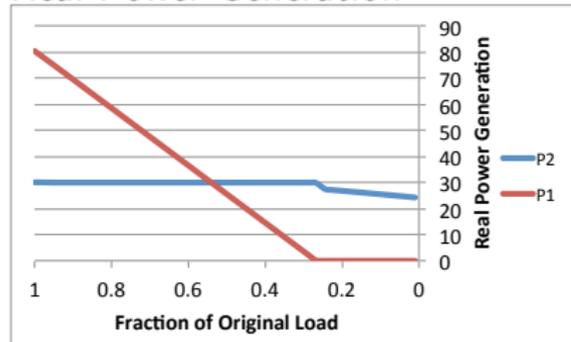
- Introduction
- DC Example: Fixing line violations
- AC Example: 2 Bus Network
- AC Example: 3 Bus Network
- Conclusion

Two Bus Network, at Normal Load

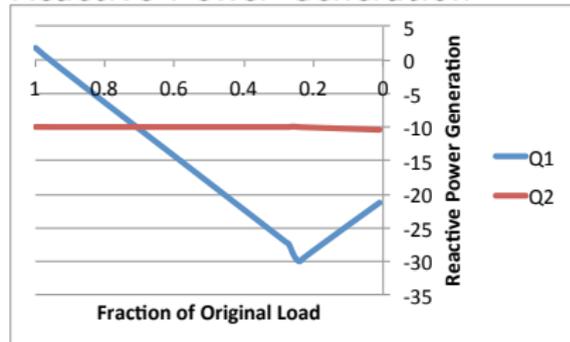


2 Bus Network, as Load Decreases: Power

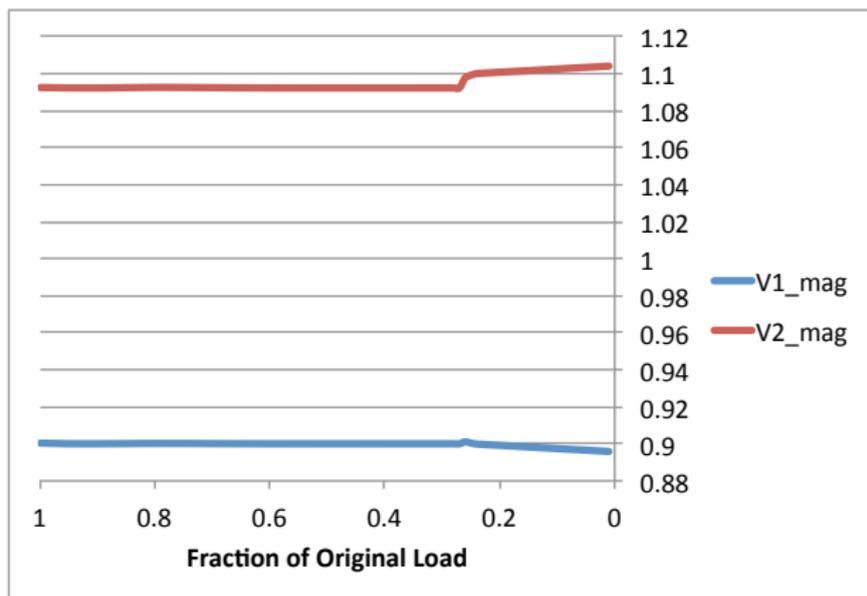
Real Power Generation



Reactive Power Generation

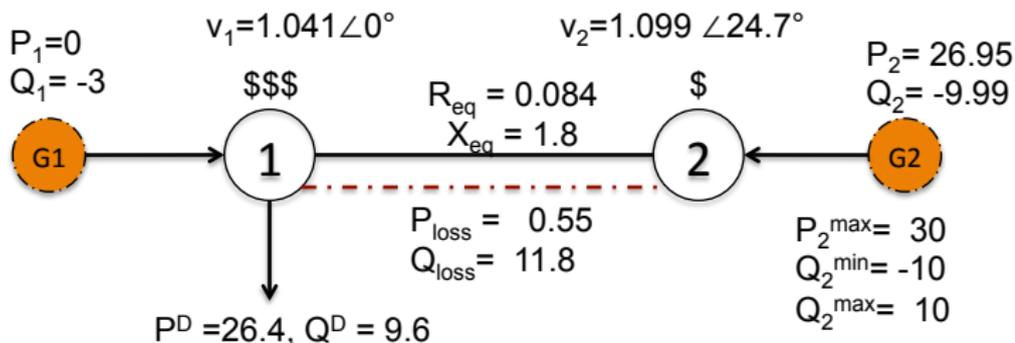
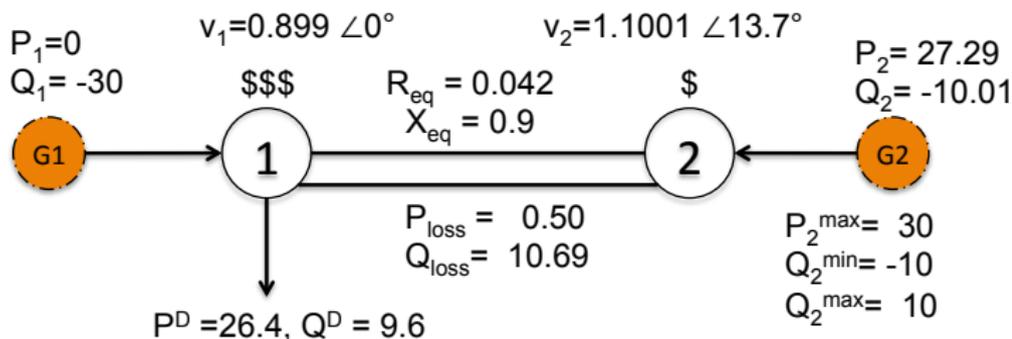


2 Bus Network, as Load Decreases: Voltage



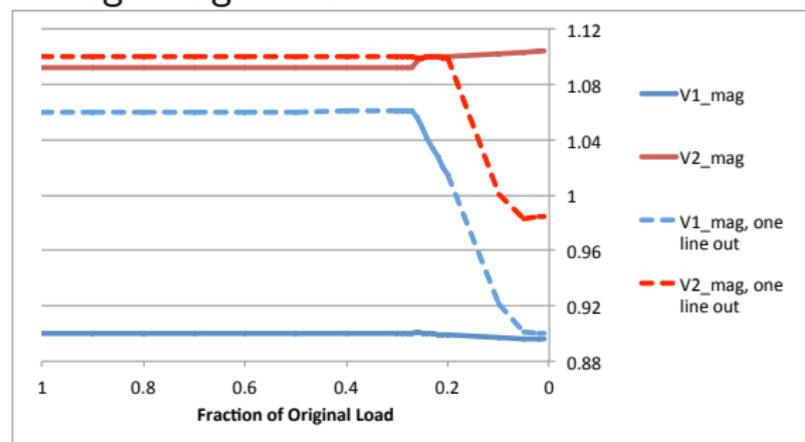
Angle difference stays at 15.3° until $p_D < 28$.
Minimum and maximum voltage violations!

2 Bus Network: Does Corrective Switching Help?

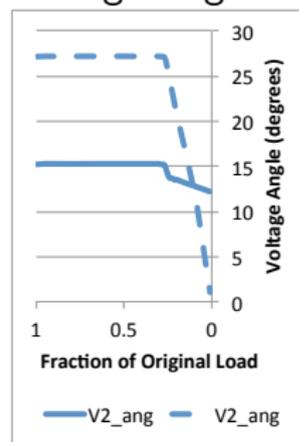


2 Bus Network: Behavior With and Without Corrective Switching

Voltage Magnitude



Voltage Angle

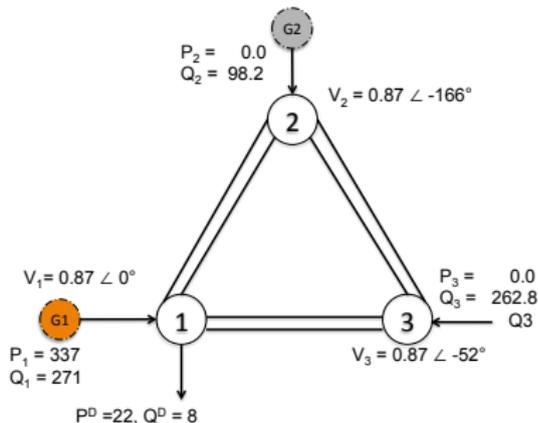
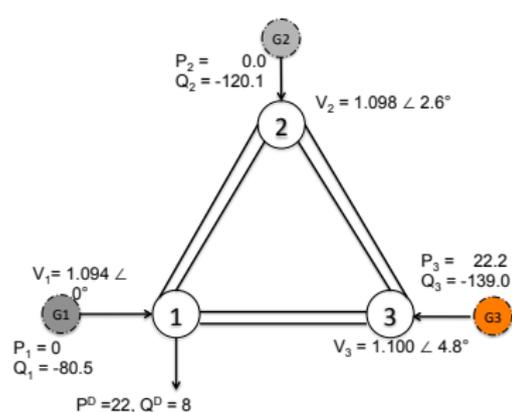


Corrective switching reduces the voltage magnitude difference, allowing the voltages to stay within bounds.

Outline

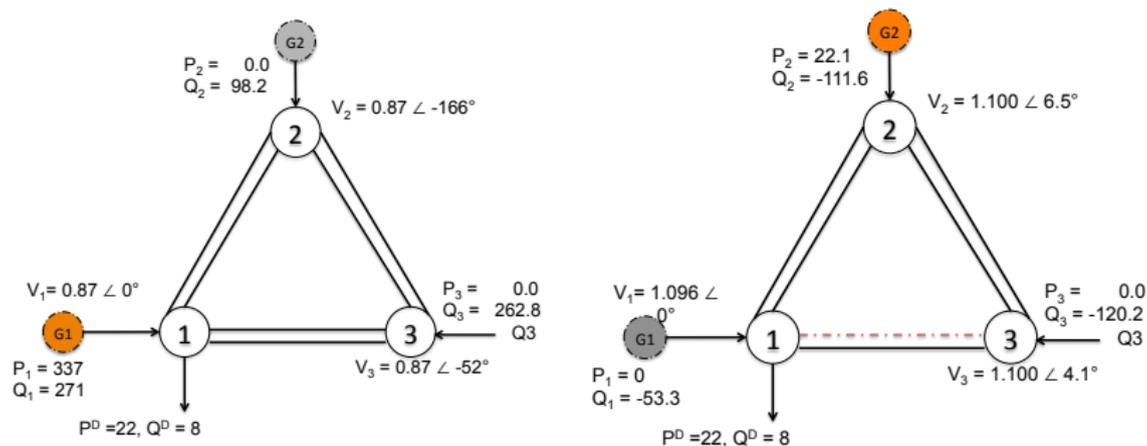
- Introduction
- DC Example: Fixing line violations
- AC Example: 2 Bus Network
- AC Example: 3 Bus Network
- Conclusion

3 Bus Network: Generator Contingency



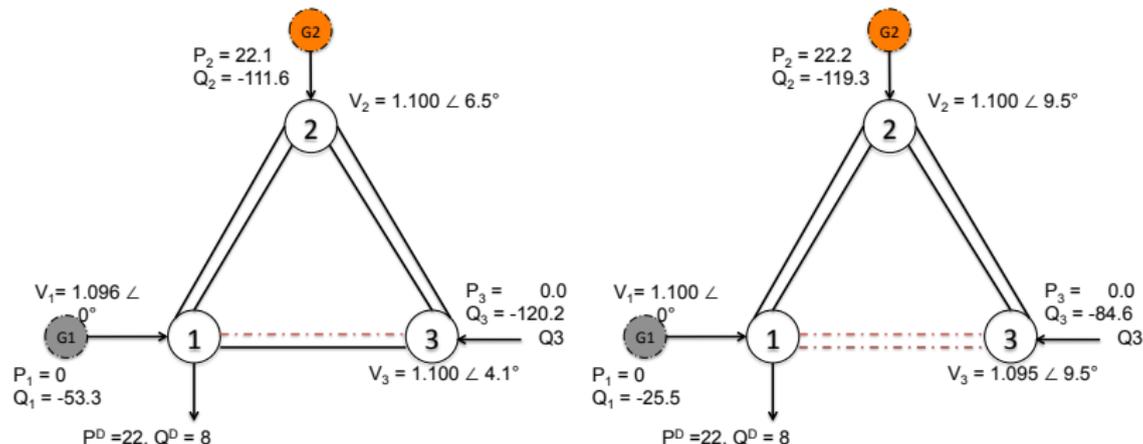
Voltage violations and nonsensical dispatch when real power cannot be produced at bus 3!

3 Bus Network: Corrective Switching with One Line



By removing one line, the voltage at each bus is raised. Reactive power with corrective switching is lower than in the pre-contingency case.

3 Bus Network: Corrective Switching with Two Lines (One Connection)



Removing an additional line increases the voltage angle difference between 1 and 2 and 1 and 3. Reactive power drops at nodes 1 and 3.

Conclusion

Switching out a line has a number of effects . . .

- Modifying the admittance of the network
- Change voltage magnitude
- Change voltage angle

Sources I

-  J. Ford, H. Bevrani, and G. Ledwich, “Adaptive load shedding and regional protection,” *International Journal of Electrical Power & Energy Systems*, vol. 31, no. 10, pp. 611 – 618, 2009. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S014206150900091X>
-  J. Momoh, M. Elfayoumy, and W. Mittelstadt, “Value-based reliability for short term operational planning,” *IEEE Transactions on Power Systems*, vol. 14, no. 4, pp. 1533–1542, Nov 1999.

Sources II

-  F. Capitanescu, J. M. Ramos, P. Panciatici, D. Kirschen, A. M. Marcolini, L. Platbrood, and L. Wehenkel, “State-of-the-art, challenges, and future trends in security constrained optimal power flow,” *Electric Power Systems Research*, vol. 81, no. 8, pp. 1731 – 1741, 2011. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378779611000885>
-  C. Liu, J. Wang, and J. Ostrowski, “Heuristic prescreening switchable branches in optimal transmission switching,” *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2289–2290, Nov 2012.

Dealing with MIP Complexity: Switching Sequence

- Opening and closing circuit breakers takes time
- Want to keep the system stable at all times
- Return a switching sequence, not just sets of lines to open/close
- Extra benefit: reduces solution time greatly

ACOPF IV Rectangular Formulation

$$i_{nmk}^r = g_{nmk} (v_n^r - v_m^r) - b_{nmk} \left(v_n^j - v_m^j \right)$$
$$i_{nmk}^j = b_{nmk} (v_n^r - v_m^r) + g_{nmk} \left(v_n^j - v_m^j \right)$$

Line Current Defn

$$i_n^r = \sum_{mk} i_{nmk}^r + g_{n0} v_n^r - b_{n0} v_n^j$$
$$i_n^j = \sum_{mk} i_{nmk}^j + g_{n0} v_n^j + b_{n0} v_n^r$$

Nodal Current Defn

$$(v_n^{\min})^2 \leq (v_n^r)^2 + (v_n^j)^2 \leq (v_n^{\max})^2$$

Nodal Voltage Limits

$$(i_{nmk}^r)^2 + (i_{nmk}^j)^2 \leq (i_{nmk}^{\max})^2$$

Line Current Limits

$$p_n^G = v_n^r i_n^r + v_n^j i_n^j + p_n^D$$

Generator Production

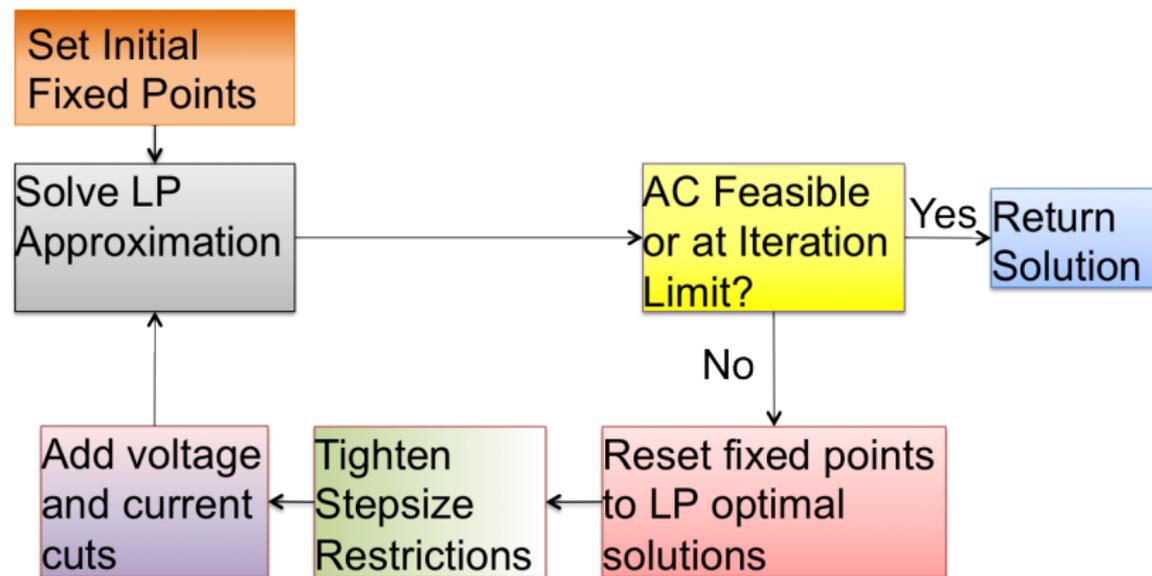
$$q_n^G = v_n^j i_n^r - v_n^r i_n^j + q_n^D$$

$$p_n^{G,\min} \leq p_n^G \leq p_n^{G,\max}$$

$$q_n^{G,\min} \leq q_n^G \leq q_n^{G,\max}$$

Gen. Production Limits

Proposed Approach



ACOPF IV LP Corrective Switching Modifications

u_n = real power load shed at bus n

w_n = reactive power load shed at bus n

c_n^u = cost of real power load shed at bus n

c_n^w = cost of reactive power load shed at bus n

ACOPF IV LP Corrective Switching Modifications

$$\text{Min} \sum_n c_n^u u_n + c_n^w w_n + \sum_{nmk} c_{nmk}^z (1 - z_{nmk})$$

$$p_n^{G, \text{approx}} = \hat{v}_n^r i_n^r + \hat{v}_n^j i_n^j + v_n^r \hat{i}_n^r + v_n^j \hat{i}_n^j - \left(\hat{v}_n^r \hat{i}_n^r + \hat{v}_n^j \hat{i}_n^j \right) + p_n^D - u_n$$

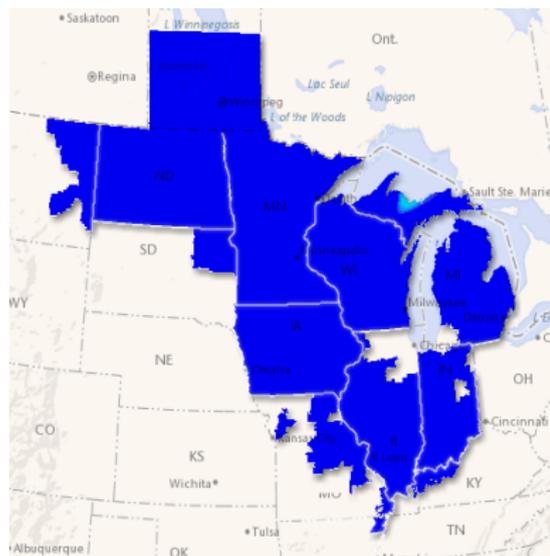
$$q_n^{G, \text{approx}} = \hat{v}_n^j i_n^r - \hat{v}_n^r i_n^j + v_n^j \hat{i}_n^r - v_n^r \hat{i}_n^j - \left(\hat{v}_n^j \hat{i}_n^r - \hat{v}_n^r \hat{i}_n^j \right) + q_n^D - w_n$$

$$0 \leq u_n \leq p_n^D$$

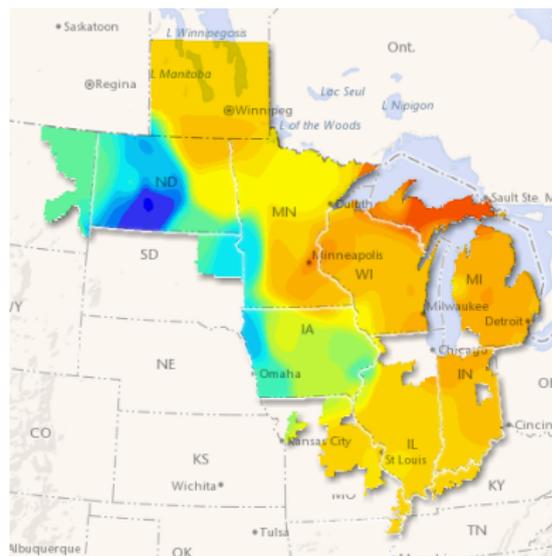
$$0 \leq w_n \leq q_n^D$$

Impact of Transmission Constraints

Very Low Congestion

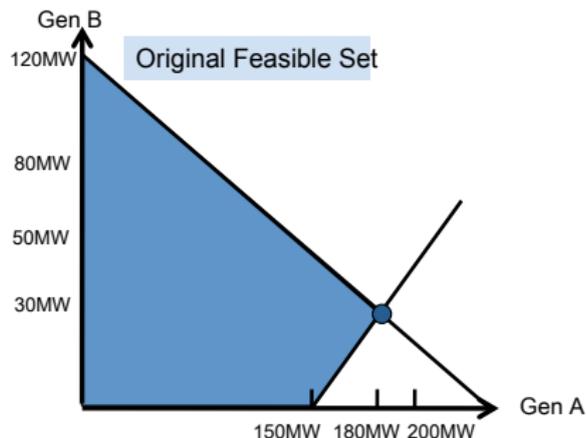
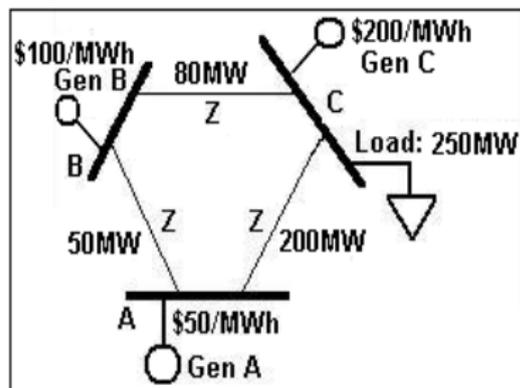


High Congestion



The Impact of Transmission Switching: Low Load

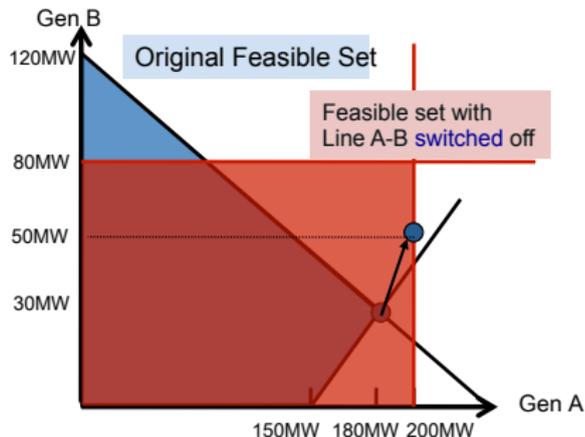
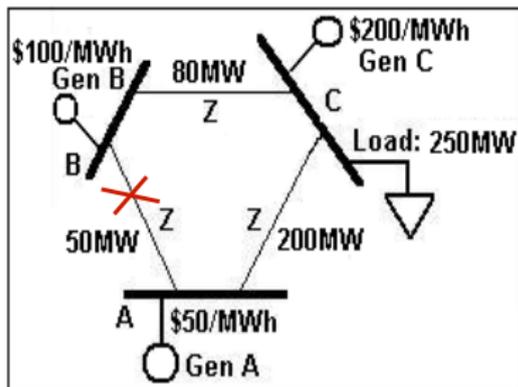
	Gen A MW	Gen B MW	Gen C MW	Total Cost
Original	180	30	40	\$ 20,000



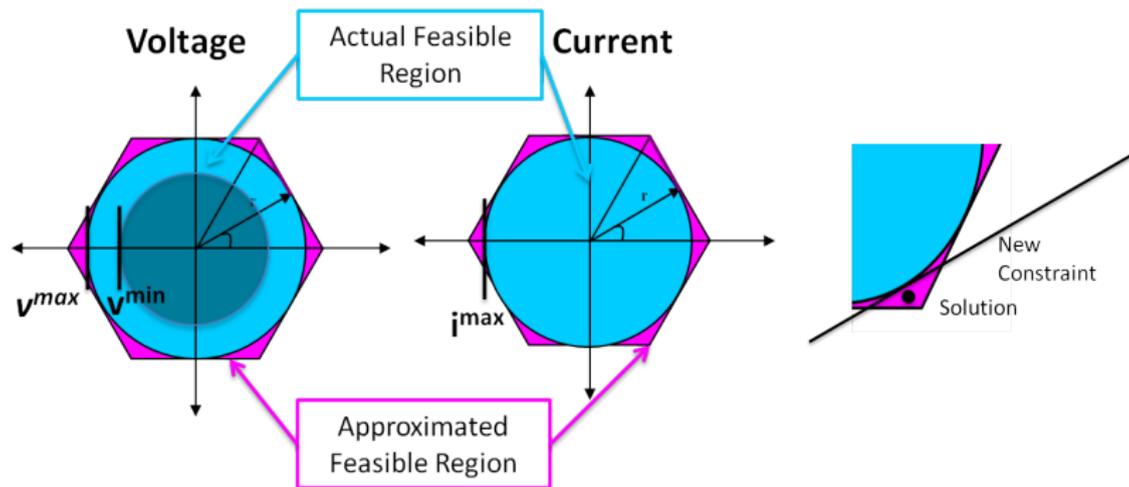
$$\begin{aligned}
 p_{k(n,m)} &= v_n^2 g_{k(n,m)} - v_n v_m (g + k(n,m) \cos(\theta_{nm}) - b_{k(n,m)} \sin(\theta_{nm})) \\
 q_{k(n,m)} &= -v_n^2 (b_{k(n,m)} + b_k^{sh}) + u_n u_m b_{k(n,m)} \cos(\theta_{nm}) - v_n v_m g_{k(n,m)} \sin(\theta_{nm}) \\
 p_{k(m,n)} &= v_m^2 g_{k(n,m)} - v_n v_m (g + k(n,m) \cos(\theta_{nm}) + b_{k(n,m)} \sin(\theta_{nm})) \\
 q_{k(m,n)} &= -v_m^2 (b_{k(n,m)} + b_k^{sh}) + u_n u_m b_{k(n,m)} \cos(\theta_{nm}) + v_n v_m g_{k(m,n)} \sin(\theta_{nm})
 \end{aligned}$$

The Impact of Transmission Switching: Low Load

	Gen A MW	Gen B MW	Gen C MW	Total Cost
Original	180	30	40	\$ 20,000
Open Line A-B	200	50	0	\$ 15,000



Convex Constraints: Visualization

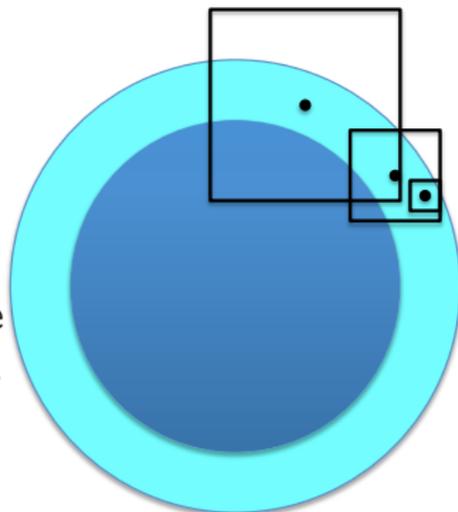


Trust Region Methods

$$-a \frac{v_n^{\max}}{h^b} \leq v_n^r - \hat{v}_n^r \leq a \frac{v_n^{\max}}{h^b}$$
$$-a \frac{v_n^{\max}}{h^b} \leq v_n^j - \hat{v}_n^j \leq a \frac{v_n^{\max}}{h^b}$$

Restricting nodal voltages also restricts line and nodal currents. If $\delta = a \frac{v_n^{\max}}{h^b}$, we can state the error bounds of p_n and q_n .

$$|p_n - p_n^{\text{approx}}| \leq 4\delta^2 (|g_{nn}| + |b_{nn}|)$$
$$|q_n - q_n^{\text{approx}}| \leq 4\delta^2 (|g_{nn}| + |b_{nn}|)$$



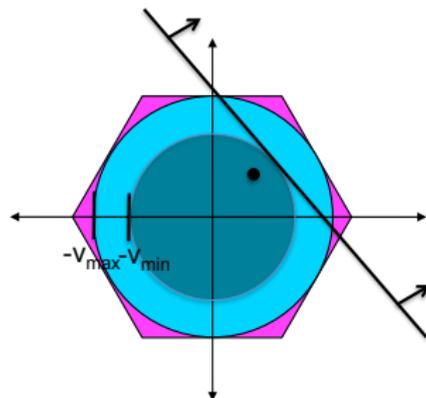
Nonconvex Constraints: Inner Voltage Constraint

Original

$$(v_n^r)^2 + (v_n^j)^2 \geq -v_n^{viol,+} + (v_n^{min})^2$$

Linearization:

$$v_n^r \hat{v}_n^{r-} + v_n^j \hat{v}_n^{j-} + \tau_n^2 \geq (v_n^{min})^2$$



Dealing with MIP Complexity: Reducing Lines Under Consideration

Economic Criteria: Liu [4]

- Solve a fixed network DCOPF
- Enforce $N - 1$ reliability for switched lines
- Create a priority list (two different criteria)
 - Smallest change in congestion of monitored lines
 - Greatest decrease in dispatch cost

Not $N - 1$ reliable



$N - 1$ reliable



Dealing with MIP Complexity: Reducing Lines Under Consideration - Liu [4] Results

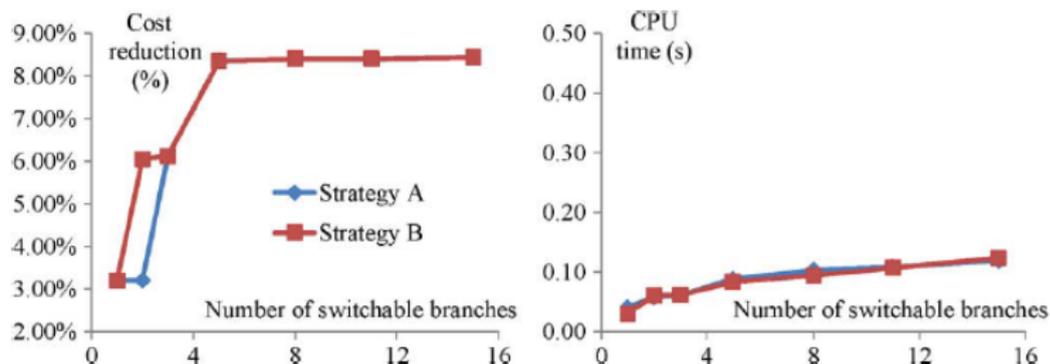


Fig. 3. Cost savings and CPU times in the case of RTS96 system.

Literature Gaps

- AC feasibility from the start
- AC Network changes with lines/generators out
- Reactive support ignored
- Localized Stability
- Robust analysis of cascading failures
- Increasing line ratings temporarily

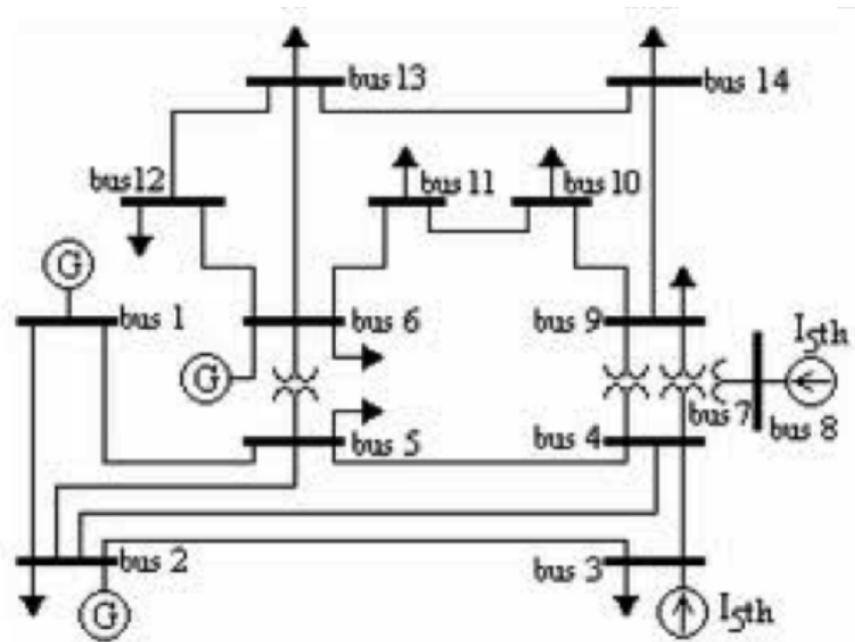
Plan: Solve with AC feasibility

Address

- AC feasibility from the start
- AC Network changes with lines/generators out
- Reactive support ignored
- Localized Stability

Background

Power Networks



Linear Constraints

$$i_{nmk}^r = g_{nmk} (v_n^r - v_m^r) - b_{nmk} (v_n^j - v_m^j)$$

$$i_{nmk}^j = b_{nmk} (v_n^r - v_m^r) + g_{nmk} (v_n^j - v_m^j)$$

$$i_n^r = \sum_{mk} i_{nmk}^r + g_{n0} v_n^r - b_{n0} v_n^j$$

$$i_n^j = \sum_{mk} i_{nmk}^j + g_{n0} v_n^j + b_{n0} v_n^r$$

If line z_{nmk} is out, $i_{nmk}^r = 0$, $i_{nmk}^j = 0$.

Convex Constraints: Formulation

Original:

$$\begin{aligned}(v_n^r)^2 + (v_n^j)^2 &\leq (v_n^{\max})^2 + v_n^{\text{viol},+} \\ (i_{nmk}^r)^2 + (i_{nmk}^j)^2 &\leq z_{nmk} (i_{nmk}^{\max})^2 + i_{nmk}^{\text{viol},+}\end{aligned}$$

Initial (Preprocessed) Linearized Constraints:

$$\begin{aligned}-v_n^{\text{viol},-} + (v_n^{\min})^2 &\leq v_n^r \hat{v}_n^{rf} + v_n^j \hat{v}_n^{jf} \leq (v_n^{\max})^2 + v_n^{\text{viol},+} \\ i_{nmk}^r \hat{i}_{nmk}^{rf} + i_{nmk}^j \hat{i}_{nmk}^{jf} &\leq z_{nmk} (i_{nmk}^{\max})^2 + i_{nmk}^{\text{viol},+}\end{aligned}$$

Iterative Constraints:

$$\begin{aligned}-v_n^{\text{viol},-} + (v_n^{\min})^2 &\leq \hat{v}_n^r \hat{v}_n^{rh} + v_n^j \hat{v}_n^{jh} \leq (v_n^{\max})^2 + v_n^{\text{viol},+} \\ i_{nmk}^r \hat{i}_{nmk}^{rh} + i_{nmk}^j \hat{i}_{nmk}^{jh} &\leq z_{nmk} (i_{nmk}^{\max})^2 + i_{nmk}^{\text{viol},+}\end{aligned}$$

Nonconvex Constraints: Real and Reactive Power

Original:

$$p_n^G = v_n^r i_n^r + v_n^j i_n^j + p_n^D$$

$$q_n^G = v_n^j i_n^r - v_n^r i_n^j + q_n^D$$

Linearization: 1st Order Taylor Series Approximation

$$p_n^{G,approx} = \hat{v}_n^r i_n^r + \hat{v}_n^j i_n^j + v_n^r \hat{i}_n^r + v_n^j \hat{i}_n^j - \left(\hat{v}_n^r \hat{i}_n^r + \hat{v}_n^j \hat{i}_n^j \right) + p_n^D$$

$$q_n^{G,approx} = \hat{v}_n^j i_n^r - \hat{v}_n^r i_n^j + v_n^j \hat{i}_n^r - v_n^r \hat{i}_n^j - \left(\hat{v}_n^j \hat{i}_n^r - \hat{v}_n^r \hat{i}_n^j \right) + q_n^D$$